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EXPERIMENTAL AND NUMERICAL EVALUATION OF DUAL PHASE FLOW DURING LIQUID INJECTION IN A COARSE SAND

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ABSTRACT

Leachate recirculation in municipal solid waste (MSW) landfills is a relatively common operational method for managing leachate and to accelerate the biodegradation of MSW for enhanced gas production (and energy recovery). However, one of the key concerns related to the addition of leachate in landfills is the increase in liquid and gas pressures if the gas extraction system cannot keep up with the enhanced gas generation. Slope stability of the landfill can be jeopardized if the fluid pressures are excessive. Dual phase models are required to evaluate the fluid pressures in a landfill subjected to leachate or liquid injection and to design a gas extraction system that couples the effects of leachate recirculation. However, there is lack of validated dual phase models for such applications. Hence, we designed and fabricated a large-scale lab model, 86 cm long × 30 cm wide × 56 cm high and made of plexiglass, to simulate the hydraulics of subsurface liquid injection. This physical scale model was filled with poorly graded coarse Ottawa sand. The saturated and unsaturated hydraulic properties of the sand were fully characterized. De-ionized (DI) water, injected in a horizontal perforated pipe installed in the sand, operated at constant flux using a high precision miniature gear pump. A 3.8 cm thick drainage layer made up of pea gravel was placed at the lower boundary of the model to create a free drainage boundary. The sand was instrumented with pressure transducers to measure pressure heads and time-domain reflectometry (TDR) sensors to monitor water contents. The numerical model Transport of Unsaturated Groundwater and Heat (TOUGH) was used to predict the fluid pressures. TOUGH was able to predict the magnitude of the air pressure buildup as a result of liquid injection However, TOUGH was not able to accurately predict the duration of air-pressure dissipation.

INTRODUCTION

In 1976, EPA enforced RCRA subtitle D for MSW landfills in order to decrease groundwater contamination and minimize human health hazards. Consequently, to reduce environmental pollution and meet EPA compliance criterion, MSW landfill operators have adopted an innovative technology of leachate recirculation to manage landfill leachate (Benson et al., 2007). Vertical wells, horizontal trenches, and permeable blankets are popular subsurface leachate-recirculation technologies to manage leachate by operating landfills as "bioreactors" (Reinhart, 1996; Haydar and Khire, 2005; Khire and Mukherjee, 2007). Bioreactor technology offers financial gain for landfill operators in the form of reduced offsite leachate treatment cost. Recently, significant research has focused on the design of these subsurface liquid-injection systems for landfills operated as a bioreactor. The underlying assumption in all these studies had been a fully vented porous medium with the gas component as a passive phase (McCreanor and Reinhart, 2000; Haydar and Khire, 2005; Khire and Mukherjee, 2007; Jain et al., 2010)—which may not be valid in real-life conditions.

Under static conditions, the liquid within the solid-waste pores is in hydraulic equilibrium with the atmosphere. Waste produces methane, carbon dioxide, and xeno-biotic gases within the landfill (Barlaz et al., 2002). These continuously generated gases are unable to fully escape the solid-waste matrix unless the gas extraction system has an efficiency of 100%, contributing to a buildup of pressure within the landfill. For example, Dona Juana landfill failure (Merry et al., 2005) was attributed to undissipated excessive pore-gas pressures within the landfill. Thus, geo-environmental designs that are unsafe due to ignoring the effect of gas components have resulted in unprecedented loss of human lives and public property. Scant literature is available on the design and operation of bioreactor landfills as a multicomponent, multiphase porous media. Hence, to study the pore-water pressure and gas-pressure distribution within a bioreactor landfill, we custom-built a large-scale landfill model to represent a leachate recirculation system. The model consisted of an 86 cm long × 30 cm wide × 56 cm high plexiglass box (Figure 1). The box consisted of an injection pipe at the top and two exit outlet pipes at the bottom. The pipes were perforated for free flow of water. The bottom of the box was sloped at 3% to exit pipes. Additionally, piezometer tubes were installed at the exit pipes to measure the pressure head buildup in the leachate collection system (LCS). The water in the tubes always remained at zero level during the experiment, verifying a fully vented condition. Additional details of the laboratory model are presented in Mukherjee and Khire (2012).

ELECTRONIC SENSORS

Automated electronic sensors were installed to measure the pressure head and volumetric water content of porous media during the experiment. The electronic sensors consisted of (1) a liquid flow sensor, (2) pressure transducers with built-in thermistors; and (3) time domain reflectometry (TDR-based) water-content sensors. Datalogger and multiplexer were programmed to automatically record data from the sensors at a constant time interval of 60 s. A detailed description of the sensors is presented in Mukherjee and Khire (2012).

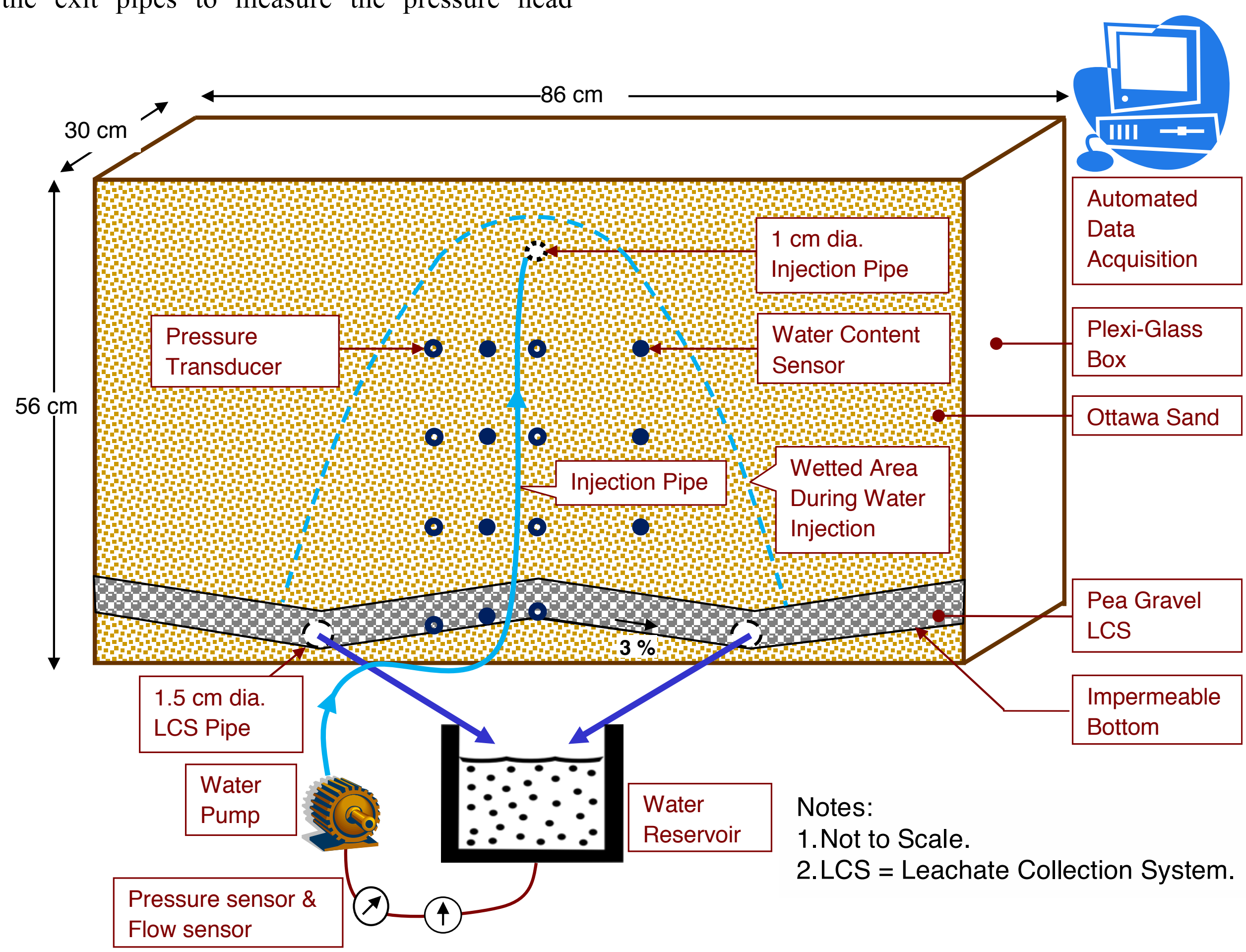

Figure 1. Large-scale leachate recirculation tank

Table 1. Properties of soils used in the physical model (Mukherjee and Khire, 2012)

Soil Type	Grain Size Distribution				Saturated and Unsaturated Hydraulic Properties				
	D_{50} (mm)	C_u	C_c	ρ_d (g/cm^3)	K (cm/s)	θ_s	θ_r	α (1/cm)	n
Ottawa Sand	0.35	2.04	1.4	1.60	$3.5\text{x}10^{-2}$	0.4	0.03	0.023	4.5
Pea Gravel	2.84	1.68	0.96	1.55	2.0	0.43	0.01	0.45	3.3

Note: D_{50} = diameter at 50% finer; C_u = co-efficient of uniformity;
C_c = co-efficient of curvature; ρ_d = dry density; K = saturated hydraulic conductivity

LABORATORY EXPERIMENT

Materials

To ensure homogeneity and isotropy of the test domain for the numerical model validation, uniformly graded Ottawa sand and washed Pea gravel were used in the experiment to simulate MSW and LCS, respectively. van Genuchten-Maulem (van Genuchten, 1980) curve fitting parameters were used to characterize the unsaturated hydraulic properties of the sand and gravel as per the following equations.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} \tag{1}$$

$$k_l = \frac{\left\{1 - (\alpha h)^{nm}[1 + (\alpha h)^n]^{-m}\right\}^2}{[1 + (\alpha h)^n]^{m/2}} \tag{2}$$

$$k_l = 1 - k_g \tag{3}$$

where θ = volumetric water content; θ_r = residual volumetric water content; θ_s = saturated volumetric water content; h= matric suction; α, n, and m are curve fitting parameters; k_l (k_g) = relative unsaturated hydraulic conductivity of liquid (gas) phase. The grain-size parameters and hydraulic characteristics of soils are presented in Table 1.

Experimental Parameters

Pea gravel simulating LCS was 3.8 cm thick. It was overlain by 46 cm of Ottawa sand. A 0.2 cm thick nonwoven geo-textile fabric separated the sand from the pea gravel underneath. The fabric prevented sand washing into gravel pores. The hydraulic conductivity of the fabric was 0.3 cm/s (ASTM D 4491). Eight pressure transducers were embedded in two vertical rows in the sand and gravel. Similarly, seven water content sensors were embedded in two vertical rows as shown in Figure 1. Note that the water content and pressure sensors were placed along the same horizontal plane. A small piece of geotextile, wrapped around the tip of each pressure sensor, prevented sand particles from falling onto the sensor diaphragm. The PVC injection pipe ran parallel to the width of the model, ensuring a uniform wetting front in the horizontal plane and a two-dimensional water injection event. De-ionized (DI) water was pumped through the injection pipe with the help of a small DC pump. The voltage of the DC pump was adjusted to control the flow of water to a constant injection flux of about 5.3 L/min. Water exiting the landfill model through bottom pipes was collected in a reservoir tank and re-injected into the sand layer.

NUMERICAL MODELING USING TOUGH

The TOUGH code developed by Pruess et al. (1999) was used to simulate the two-phase hydraulics of the water-recirculation experiment. The landfill model was conceptualized as a two-dimensional rectangular domain in TOUGH. Injection flux measured by the flow sensor was used as the time-varying source term at injection pipe. The bottom boundary was kept at constant atmospheric pressure and at a fixed liquid saturation of 0.999. The bottom boundary with two perforated pipes (with the rest of the boundary being impermeable) could not be simulated in the version of TOUGH we used. The top boundary was defined as air permeable, maintained at a constant atmospheric pressure, and also water impermeable. All other boundaries were assigned as no-flow boundaries. Atmospheric pressure was assumed as the reference pressure. Isothermal conditions at 20°C were assumed.

RESULTS AND DISCUSSION

DI water was injected into the model at a constant flux of about 5.3 L/min. Electronic pressure transducers and TDRs were used to monitor the water pressures and water contents.

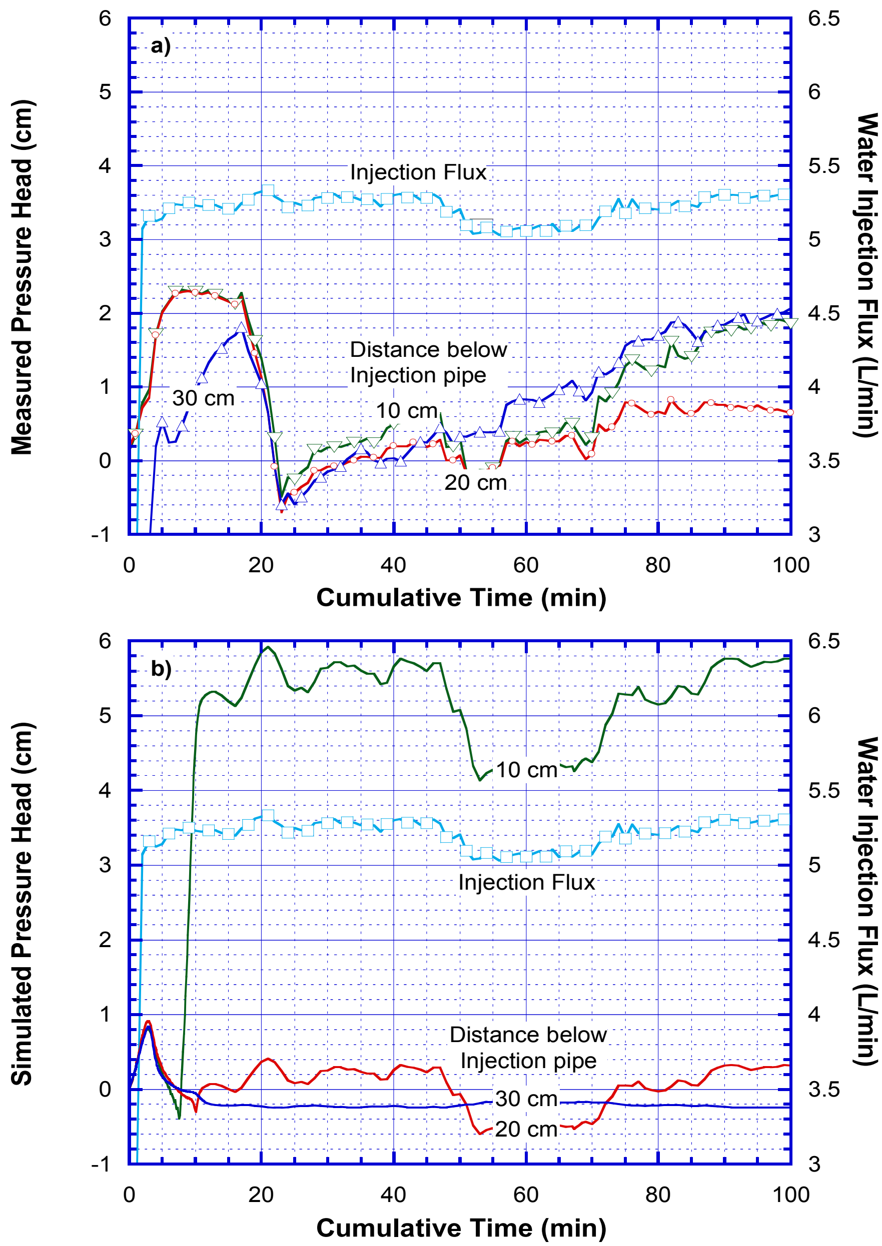

Figure 2. Measured (a); and simulated (b) pressure heads in recirculation experiment

Water Recirculation Lab Experiment

The water-injection experiment lasted a total of two weeks. Immediately after the injection started, an increase in pressure was recorded by pressure transducers at all depths below the injection pipe as shown in Figure 2(a). For brevity, only pressure sensors located vertically below the injection pipe are discussed here. The water pressures at 10 cm and 20 cm below the injection pipe reached a maximum value of 2.5 cm within 7 min. The pressures started to dissipate after 17 min and rose again gradually. Lower pressure was recorded at a depth of 30 cm, with a maximum value of only 1.8 cm. Sensors at lower depths were closer to the bottom drainage boundary of the box and hence offered less resistance to entrapped air trying to escape the sand pores. Consequently, the lower sensor recorded lower pressures than the sensors near the injection pipe.

The water-content sensors located at various depths reached a steady-state value after about 11.5 days. The sensors located at 10 and 20 cm depths reached a maximum saturation of about 90%, while the deepest sensor (40 cm) reached about 100% saturation in 11.5 days (Khire and Kaushik, 2012).

The pressure heads did not completely dissipate till about 11.5 days after injection started (not shown in Figure 2). Mukherjee and Khire (2012) reported similar time frames for dissipation of air pressures for an experiment carried out using the same physical model. Wang et al. (1998) also reported an increase in air pressure and subsequent pressure drop to a minimal value for an air-confining infiltration experiment. The reason for such an air-pressure buildup has been attributed to the unconnected pores of the media and restricted hydraulic boundaries for an unrestricted exit of entrapped air in the sand.

Numerical Modeling Results

The EOS3 module in TOUGH considers air and water as active gas and liquid phase components, respectively. Hence, it was used to simulate the experiment. Figure 2(b) presents simulated pressure heads. TOUGH was able to capture the initial increase in pressure due to entrapped air, at all depths below the injection pipe. The simulated pressures increased to 0.8 cm at 3 min and dropped to zero within 10 min. The simulated pressures, while lower, are still within the same order of magnitude as the measured pressures at the corresponding depths. TOUGH predicted an early dissipation of air pressure, whereas it took about 17 min to 11.5 days for the air pressures to fully dissipate in the experiment (Khire and Kaushik, 2012). The reason for such a difference could be that dead-end pores within the sand made the time to remove trapped air longer, resulting in higher air pressures for an extended period of time. In addition, with respect to TOUGH input, the lower boundary could not be simulated as the physical setup—it consisted of two free-flowing perforated pipes, which is more restrictive for air flow than what was input into the model.

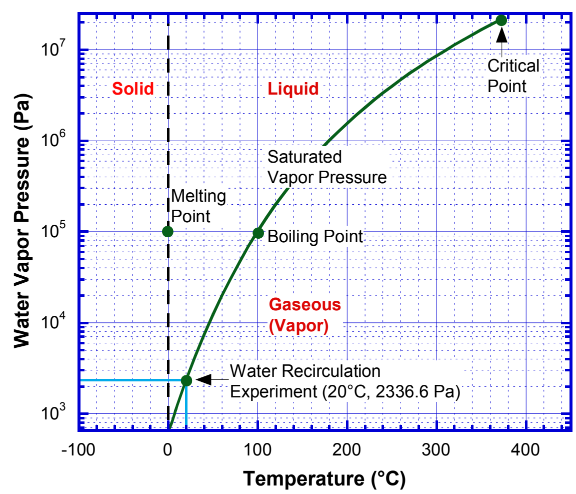

Figure 3. Water-phase diagram

TOUGH considers air and water as two components present in both liquid and gas phase. The total gas-phase pressure is calculated following Dalton's law of partial pressures:

$$P_g^{tot} = P_g^a + P_g^w \tag{4}$$

where, P_g^a = pressure in the gas phase due to air and P_g^w = water vapor pressure. For unsaturated element volume, i.e., $0 < S_l < 1$ (S_l = liquid saturation) where both liquid and gas phase coexist, P_g^w is equal to saturated vapor pressure (2336.6 Pa at 20°C temperature) as per the water-phase diagram (Figure 3).

The air pressure in gas phase (P_g^a) is calculated by Henry's law:

$$P_g^a = K_H \times X_l^a \quad (5)$$

where K_H is Henry's constant (assumed to be 10^{10} Pa/mole at all temperatures, for air-gas interface in TOUGH). X_l^a is air mass fraction of the liquid phase defined by M_l^a / M_l (M_l^a is mass of air in liquid phase and M_l is total liquid mass) and is computed from mass-balance equations in TOUGH.

As the water-injection event began, the air mass fraction in the liquid phase increased from 1.5912E-5 to a maximum 1.5927E-5 at 3 min for all depths (Figure 4). X_l^a eventually decreased to a relatively low value below the initial condition of 1.5912E-5 at all depths, which resulted in below-atmospheric gas-phase pressures.

With the onset of saturation at 7.5 min and 10 min, the air mass fraction in liquid phase dropped steeply for nodes at 10 cm and 20 cm below the injection pipe, respectively (Figures 4 and 5). On the contrary, X_l^a at 30 cm depth dropped to a constant value of 1.5908E-5, indicating a two-phase unsaturated condition. As calculated by TOUGH2, the value at 1 bar pressure and 20°C temperature is ~1.6×10^{-5}. The unsaturated conditions at 30 cm depth and saturated conditions at 10 cm and 20 cm depth are also validated by the liquid saturation plot (Figure 4). Under saturated conditions, Darcy's law was used to evaluate pressures from liquid discharge (mass), while for unsaturated conditions, X_l^a calculated at different depths was used by TOUGH to evaluate air pressure and total gas-phase pressures.

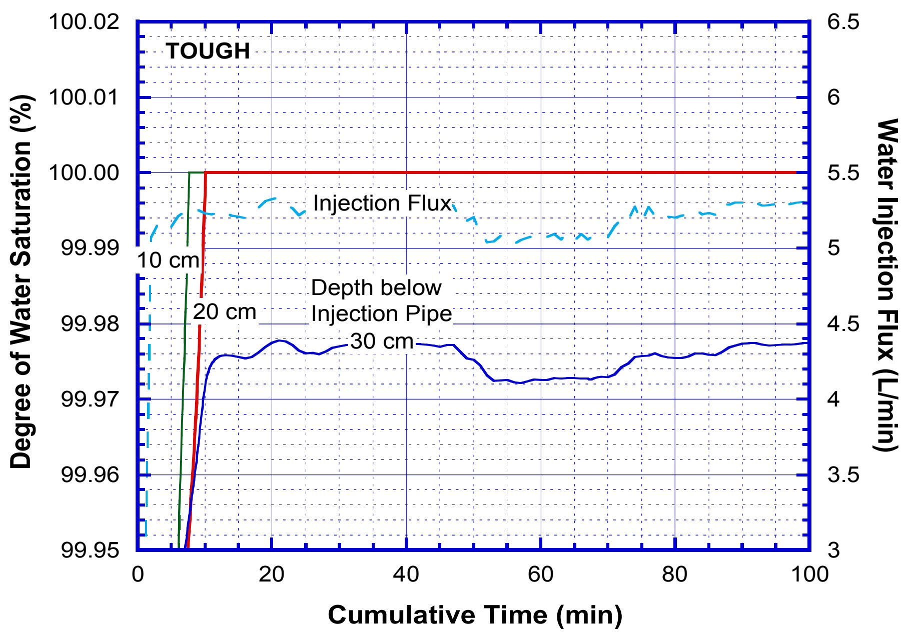

Figure 4. TOUGH simulated water saturation

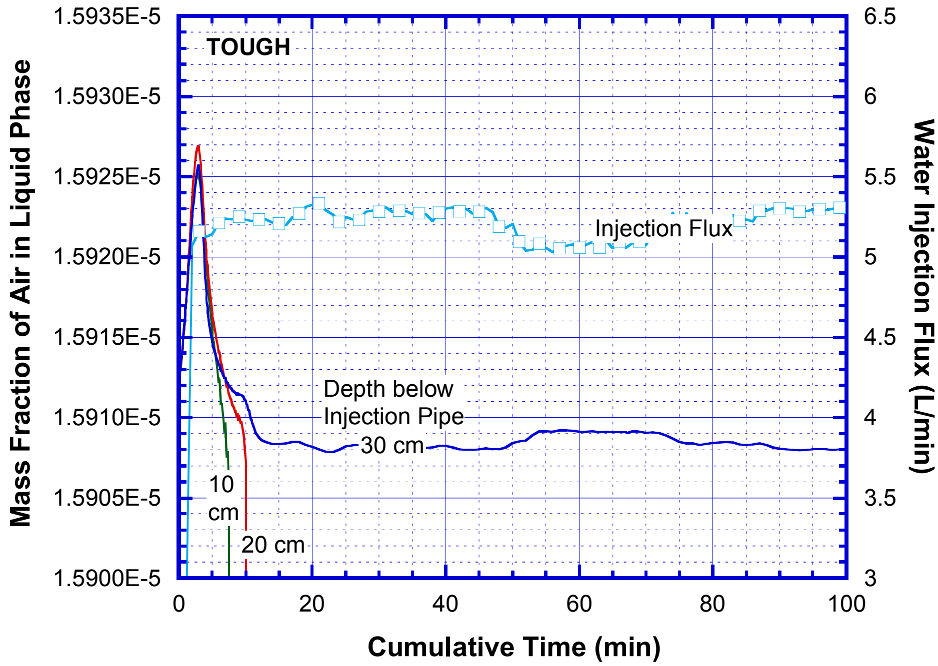

Figure 5. TOUGH simulated mass fraction of air in liquid phase

SUMMARY

Single-phase and single-component models have been commonly used to design subsurface liquid injection systems in bioreactor landfills. The underlying assumption of a passive gas phase in such models results in underestimation of fluid pressures. To assess the suitability of two-phase models such as TOUGH, a large-scale recirculation experiment was conducted using a horizontal perforated pipe, with the experiment simulated by the TOUGH code. This study resulted in the following observations:

1) TOUGH is able to simulate air-pressure increases in dry sand due to pressurized injection of water. TOUGH predicted air pressures relatively accurately.

2) TOUGH is unable to model dead end pores and the vented-perforated-pipe lower boundary in the physical model. Hence, TOUGH was not able to accurately predict the duration of air dissipation observed in the experiment.

Additional simulations using WinGridder are planned to simulate the lower boundary accurately.

ACKNOWLEDGEMENT

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REFERENCES

ASTM Standard D4491, Standard Test Methods for Water Permeability of Geotextiles by Permittivity, Book of ASTM Standards, 4(13), ASTM International, West Conshohocken, PA, 2009.

Barlaz, M. A., A. P. Rooker, P. Kjeldsen, M. A. Gabr, and R. C. Borden, Critical evaluation of factors required to terminate the post-closure monitoring period at solid waste landfills, *Envir. Sci. and Tech.*, 36 (16), 3457-3464, 2002.

Benson, C. H., M. A. Barlaz, D. T. Lane, and J. M. Rawe, Practice review of five bioreactor/recirculation landfills, *Waste Manage.*, 27, 13-29, 2007.

Haydar, M., and M. V. Khire, Leachate Recirculation Using Horizontal Trenches in Bioreactor Landfills, *J. Geotech. Geoenviron. Eng.*, 131(7), 837-847, 2005.

Jain, P., T. G. Townsend, and T. M. Tolaymat, Steady-state design of vertical wells for liquids addition at bioreactor landfills, *Waste Manage.,* 30, 2022-2029, 2010.

Khire, M. V., and M. Mukherjee, Leachate injection using vertical wells in bioreactor landfills, *Waste Manage.*, 27, 1233-1247, 2007.

Khire, M. V., and T. Kaushik, Experimental and Numerical Evaluation of Liquid Injection using Horizontal Trench System for Bioreactor Landfills, GeoCongress 2012, *ASCE Geotechnical Special Publication No. 225*, Geotechnical Engineering State of the Art and Practice, Oakland, CA, 27-29, March, 2012.

McCreanor, P. T., and D. R. Reinhart, Mathematical Modeling of Leachate Routing in a Leachate Recirculating Landfill, *Water Resour.*, 34(4), 1285-1295, 2000.

Merry, S. M., E. Kavazanjian Jr., and W. U. Fritz, Reconnaissance of the July 10, 2000, Payatas Landfill Failure, *Journal of Performance of Constructed Facilities*, 19(2), 100-107, 2005.

Mukherjee, M., and M. V. Khire, Instrumented large scale subsurface liquid injection model for bioreactor landfills, *Geo. Test. Jour.*, 35(1), 1-10, 2012.

Pruess, K., C. Oldenburg, and G. Moridis, *TOUGH2 User's Guide, Version 2.0,* Report LBNL-43134, Lawrence Berkeley National Laboratory, Berkeley, Calif., 1999.

Reinhart, D. R., Full-scale experiences with leachate recirculating landfills: case studies, *Waste Manage. And Res. (ISWA)*, 14: 347-365, 1996.

van Genuchten, M. Th., A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils, *Soil Sci. Soc. Am. J.*, 44(5), 892-898, 1980.

Wang, Z., J. Feyen, M. T. van Genuchten, and D. R. Nielsen, Air entrapment effects on infiltration rate and flow instability, *Water Resources Res.*, 34(2), 213-222, 1998.